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AUTHORS: BUNDY, GERBER AND BRADLEY

TITLE: THERMAL DISTORTION DUE TO WALL THICKNESS VARIATION AND UNEVEN COOLING IN AN M256 120-MM GUN BARREL

ABSTRACT:

During firing, the gun barrel centerline profile and muzzle pointing angle change due to thermal distortion. There are several causes of thermal distortion; we will discuss two: uneven cooling, and non-uniform wall thickness. We will briefly explain the mechanisms by which these two effects produce gun barrel bending and describe how these effects are modeled. We will demonstrate our model by predicting the muzzle pointing angle change for a particular gun tube firing five rounds, one every two minutes. The predictions are compared with experimental results; some agreement is noted.

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THERMAL DISTORTION DUE TO WALL THICKNESS VARIATION AND UNEVEN COOLING IN AN M256 120-MM GUN BARREL

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1. INTRODUCTION

High temperature propellant gas transfers heat to the barrel on every shot. If one side of the barrel has a slightly thicker wall than the other side, then the firing heat input will cause a greater change in temperature on the thin-walled side. This will produce a cross-barrel temperature difference, CBTD, which will create a non-uniform thermal expansion, and thereby bend the barrel away from the high temperature side.

Gerber and Bundy [1] computed the effect of wall thickness variation on CBTD in the 120 mm M256 gun. Their numerical model uses as input: the propellant temperature for a given 120-mm round type (e.g., DM13, M829, etc.), obtained from the NOVA code [2]; and the convection coefficient, obtained from the Veritay code [3,4], which utilizes the method of Stratford and Beavers [5]. The CBTD model will compute a non-zero temperature difference across the barrel at any point where the wall thickness is not uniform (a symmetric chrome layer is assumed).

When the firing heat input reaches the outer wall of the barrel, it will begin to transfer heat to the surrounding air. Since heated air rises in the earth's gravitational field, the hot air rising past the top of the barrel will remove less heat than the ambient temperature air moving past the bottom. And thus, a positive top-minus-bottom CBTD is established. Bundy [6] has recorded (plotted) CBTDs versus above-ambient barrel temperature at several locations along the bore. In addition, he has formulated a thermoelastic model that predicts barrel bend for any specified distribution of CBDTs along the barrel.

We will use the above two models, and reference data, to predict barrel bend due to CBDTs caused by wall thickness variation and uneven cooling for five rounds (DM13 kinetic energy penetrators) fired through a particular barrel (serial number 4251). We will compute the total muzzle angle change due to the combined CBTD effects after each shot and compare the predictions with measurements.

2. INPUT DATA:

A representative plot of the propellant gas temperature, T_g, and convection coefficient, h_g, for the DM13 round at two locations, z=2.85 m and z=4.45 m from the breech, is shown in Figures 1 and 2, respectively.

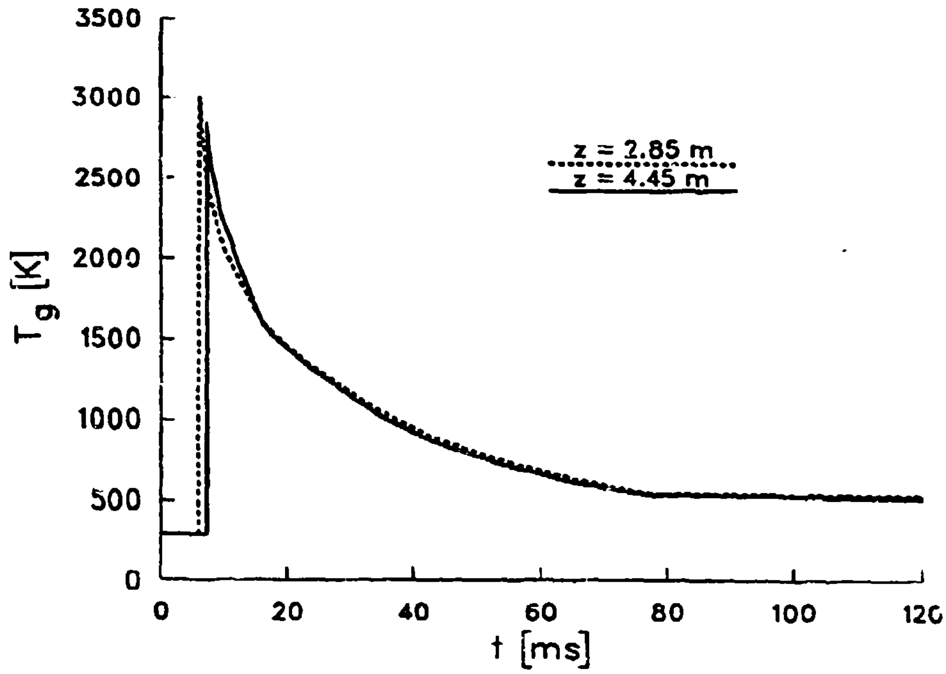

Figure 1. Propellant Gas Temperature versus Time, at z=2.85 m and z=4.45 m from the Breech, Computed from the NOVA code

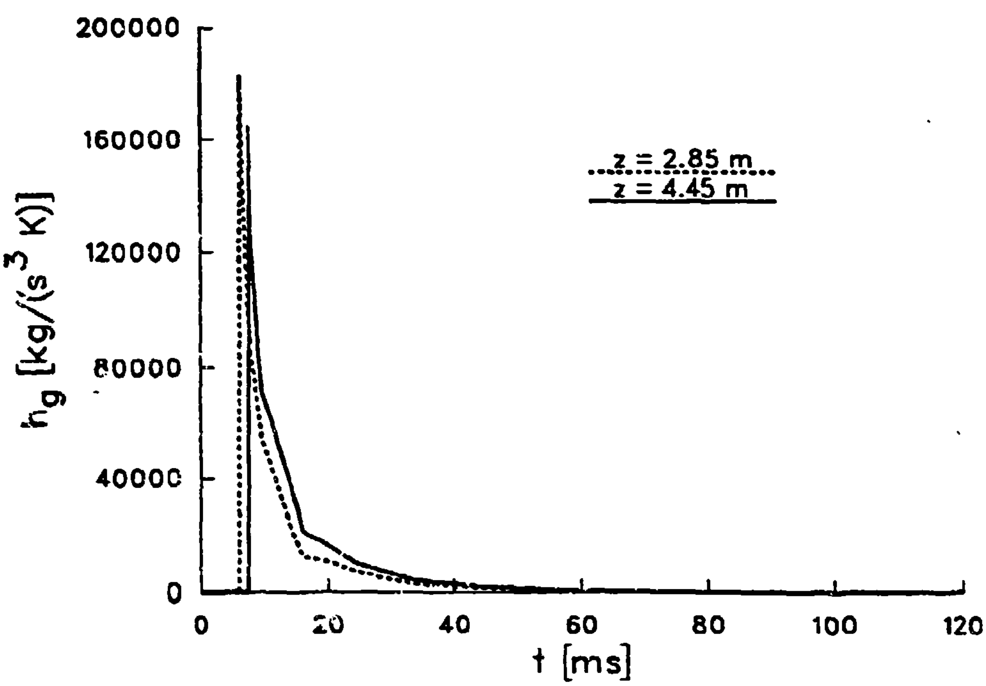

Figure 2. Heat Transfer Convection Coefficient, at z=2.85 m and z=4.45 m from the Breech, Computed from the Veritay Code

It is standard procedure at the time of manufacture to measure the inner and outer barrel radii at four positions around the bore (every 90 degrees), at numerous axial locations. Thus, wall thickness variation can be determined from these measurements. We will model wall thickness variation at a point along the bore axis by assuming that a plane, normal to the bore axis, will intersect the inner and outer walls of the barrel in two circles. The inner circle will have a radius R_i and the outer circle will have a radius R_o. Where there is wall thickness variation, the two circles will not be concentric. Viewed from the breech, we can describe the outer circle as displaced a distance ε at an angle φ relative to the origin and gunner's right of the inner circle, see Figure 3.

A listing of R_i, R_o, ε, and φ for the M256 gun barrel, serial number 4251 (manufactured in 1987), is given in Table 1. Since the barrel is relatively thick and the ε's are relatively small over that portion of the tube which lies within the recoil cradle (roughly the first two meters from the breech), we have assumed, a priori, that the majority of the thermal distortion due to wall thickness variation will originate from the region outside the cradle. Therefore, we have only specified values in Table 1 for R_i, R_o, ε, and φ over that portion of the barrel which extends beyond the recoil cradle.

The maximum value of ε for serial number 4251 is 0.13 mm, which corresponds to a maximum wall thickness variation of $2\varepsilon = 0.26$ mm. The maximum acceptable wall thickness variation for any M256 barrels is 1.5 mm (outside the chamber), which is almost six times larger than that of serial number 4251. Nevertheless, it is typical of barrels produced in recent years to have their maximum wall thickness variation several times smaller than the maximum allowed.

Table 1. Geometry for M256 Gun Barrel, Serial Number 4251

Distance, z, from Breech (m)	R_i (mm)	R_o (mm)	ε (mm)	φ (deg)
5.24	60	77.1	0.080	-128
5.09	60	77.2	0.075	-79
5.02	60	80.9	0.065	-90
4.45	60	82.7	0.100	-108
3.95	60	85.4	0.056	-63
3.45	60	109.1	0.027	-158
2.85	60	109.1	0.125	+81
2.35	60	103.0	0.130	+61

3. CBTD COMPUTATIONS

3.1 Wall Thickness Variation

Given the wall thickness variation described in Table 1, the model of Gerber and Bundy is used to calculate top-minus-bottom and left-minus-right CBDTs that result from propellant gas heating of the asymmetric barrel. For example, Figure 4 plots the CBTD history at the z=5.02 m location. From Table 1 and Figure 3, we can deduce that the bottom of the barrel is thicker than the top at z=5.02 m from the breech (φ = -90°); thus, we would expect the top-minus-bottom temperature difference to be positive, as predicted in Figure 4. Also, since the origins of the inner and outer wall radii are both aligned in the vertical plane at z=5.02 m, there should be no wall thickness variation, and hence no CBTD, in the horizontal plane, which is also shown to be the case in Figure 4.

For later comparison with experiment, we will tabulate the CBTD roughly one minute after firing each of the five rounds. These values are listed in Table 2, with the left-minus-right temperature difference denoted $CBTD_x$, and top-minus-bottom temperature difference denoted $CBTD_y$.

Table 2. Predicted CBTDs in the Horizontal and Vertical Planes Due to Wall Thickness Variation

Distance, z, from Breech (m)	$CBTD_x$ One Minute After Firing Round Number (°C)					$CBTD_y$ One Minute After Firing Round Number (°C)				
	1	2	3	4	5	1	2	3	4	5
5.24	-.07	-.13	-.16	-.18	-.19	+.10	+.16	+.21	+.23	+.25
5.09	+.03	+.04	+.05	+.06	+.06	+.11	+.19	+.24	+.27	+.29
5.02	0.00	0.00	0.00	0.00	0.00	+.07	+.11	+.15	+.17	+.19
4.45	-.02	-.04	-.05	-.06	-.07	+.08	+.13	+.17	+.19	+.21
3.95	+.01	+.03	+.03	+.04	+.04	+.03	+.05	+.07	+.08	+.08
3.45	-.01	-.01	-.01	-.01	-.02	0.00	0.00	+.01	+.01	+.01
2.85	0.00	+.01	+.01	+.01	+.01	-.03	-.05	-.07	-.08	-.09
2.35	+.02	+.03	+.04	+.05	+.06	-.04	-.06	-.07	-.09	-.10

3.2 Uneven Cooling

To estimate the top-minus-bottom CBTD due to uneven cooling one minute after firing at each of the locations in Table 1, we must first find the average above-ambient barrel temperature at each of these locations and times. This data can be obtained, and is displayed in Table 3, from the same Gerber and Bundy model used to predict the CBTDs due to wall-thickness variation.

As aforementioned, Bundy [6] has measured and plotted the CBTDs in the vertical plane due to uneven cooling as a function of the average above-ambient M256 barrel temperature. Using this reference data, we can estimate the CBTDs associated with the temperatures in Table 3. Since the data in Bundy is not given at the same locations as Table 3, we must use interpolation and extrapolation to determine the CBTD values listed here.

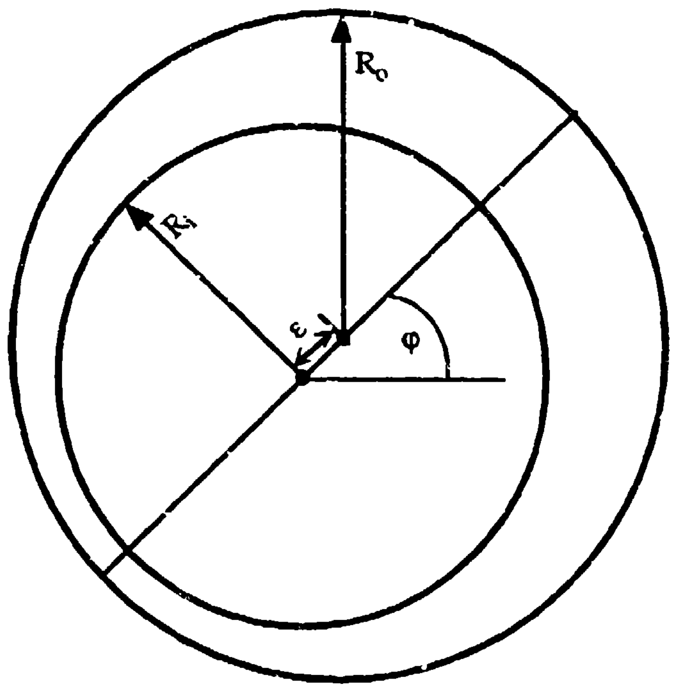

Figure 3. Transverse Cross Section of a Gun Barrel of Non-uniform Thickness, Viewed from the Breech

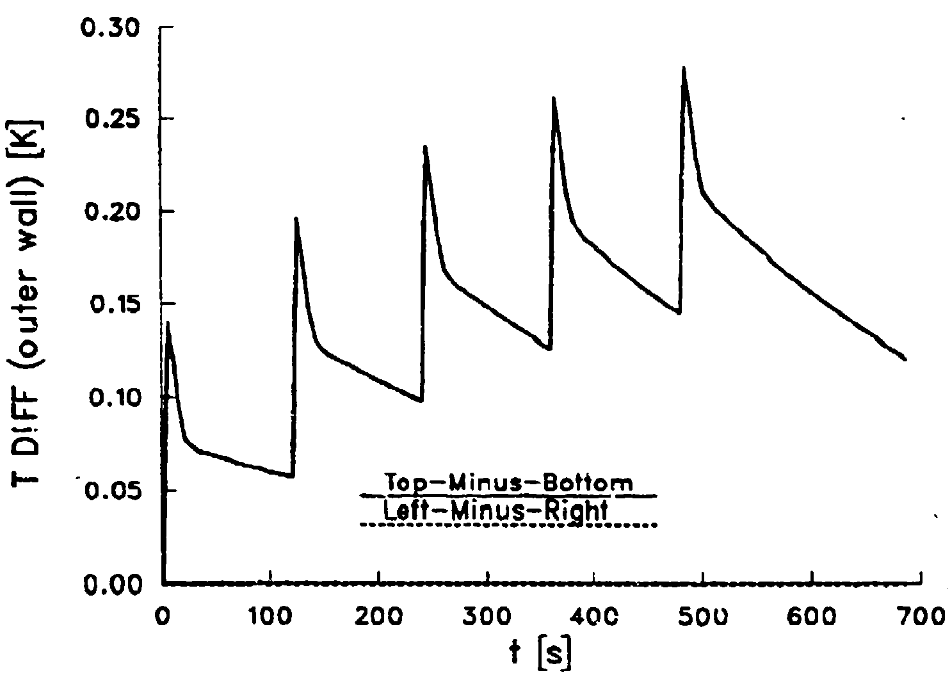

Figure 4. Predicted CBTDs in the Horizontal (Azimuthal) and Vertical (Elevation) Plane Due to Wall Thickness Variation at z=5.02 m from the Breech, from Gerber and Bundy code

Table 3. Predicted CBTDs in the Vertical Plane Due to Uneven Cooling

Distance, z, from Breech (m)	Average Above-Ambient Barrel Temperature One Minute After Firing Round Number (°C)					$CBTD_y$ One Minute After Firing Round Number (°C)				
	1	2	3	4	5	1	2	3	4	5
5.24	14	28	40	52	64	+1.8	+3.4	+4.6	+6.0	+7.2
5.09	14	28	40	52	64	+1.5	+2.8	+3.8	+4.1	+6.0
5.02	12	22	33	43	52	+1.4	+2.6	+3.5	+3.7	+5.4
4.45	10	18	26	34	42	+.30	+.40	+.55	+.75	+.90
3.95	8	15	22	29	35	+.25	+.35	+.50	+.65	+.75
3.45	3	7	10	13	16	+.16	+.25	+.35	+.45	+.53
2.85	4	7	11	14	18	+.04	+.08	+.10	+.13	+.16
2.35	5	9	13	.7	21	0.00	0.00	+.01	+.01	+.02

4. BARREL BEND

The predicted barrel bend will be determined using the model described in Bundy [6]. This model computes the barrel bend of an M256 cannon due to uneven thermal expansion associated with a given set of CBTD input values. It is based on thermoelastic theory [7], which is applicable for small bends, such as the case here. The model assumes the barrel is supported at 0.36 m and 1.52 m from the breech, which is approximately the region where the barrel is upheld in the M256 recoil cradle. The change in elastic modulus with temperature at each CBTD location can be included in the barrel bend calculations, however, Bundy has shown that for tank gun firings this has an insignificant effect.

We will first compute thermal distortion due to wall thickness variation alone. In particular, Figure 5 shows the predicted change in horizontal and vertical muzzle angle due to the CBTD pairs ($CBTD_x$ and $CBTD_y$) given in Table 2. In general the muzzle angle is predicted to move down and to the gunner's right. However, the angular changes are extremely small. For comparison, we next plot, Figure 6, the predicted change in muzzle angle due to uneven cooling, from the $CBTD_y$ values in Table 3. It can be seen that the effect of uneven cooling dwarfs that of uneven wall thickness (for this particular barrel, under these firing conditions).

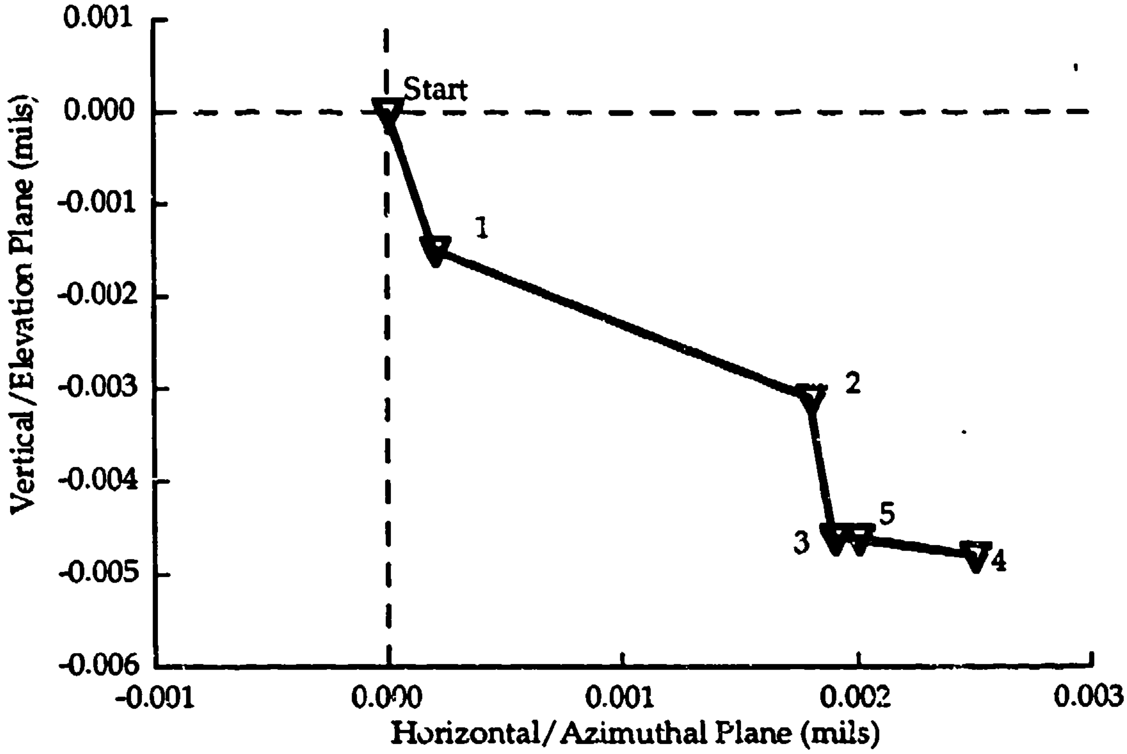

Figure 5. Predicted Muzzle Angle Change Due to Wall Thickness Variation, Associated with the CBTD Values of Table 2

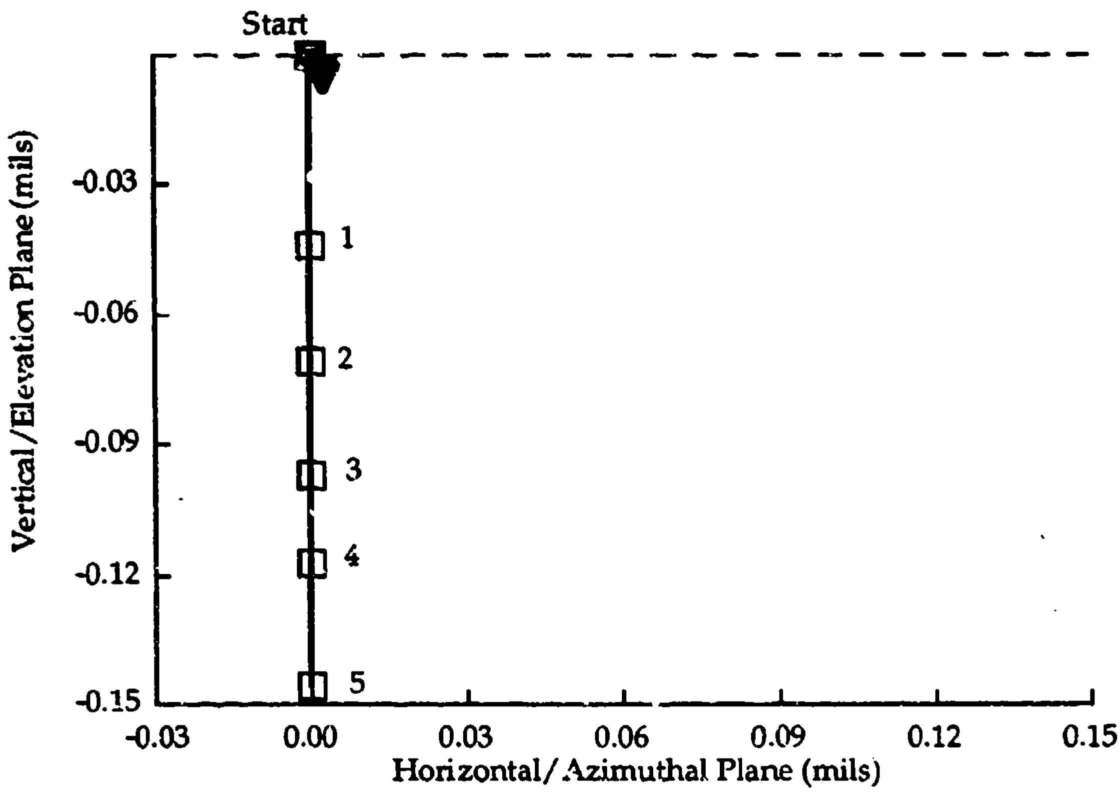

Figure 6. Predicted Muzzle Angle Change Due to Wall Thickness Variation and Uneven Cooling, Associated with the CBTD Values of Tables 2 and 3

The experimentally observed change in muzzle pointing angle at the times corresponding to Figure 6 are shown in Figure 7.* (Note, to correct for movement in the recoil cradle after firing each round, we have subtracted the angular change in the recoil cradle from the actual muzzle angle change for each measurement shown in Figure 7.) There is general agreement in the downward trend, most predictions in the vertical plane are within the experimental error of the measurements. However, in the horizontal plane the predicted movement to the gunner's right is much smaller than the measured movement to the right, nevertheless, the predictions are still within the measurement error of the instruments.

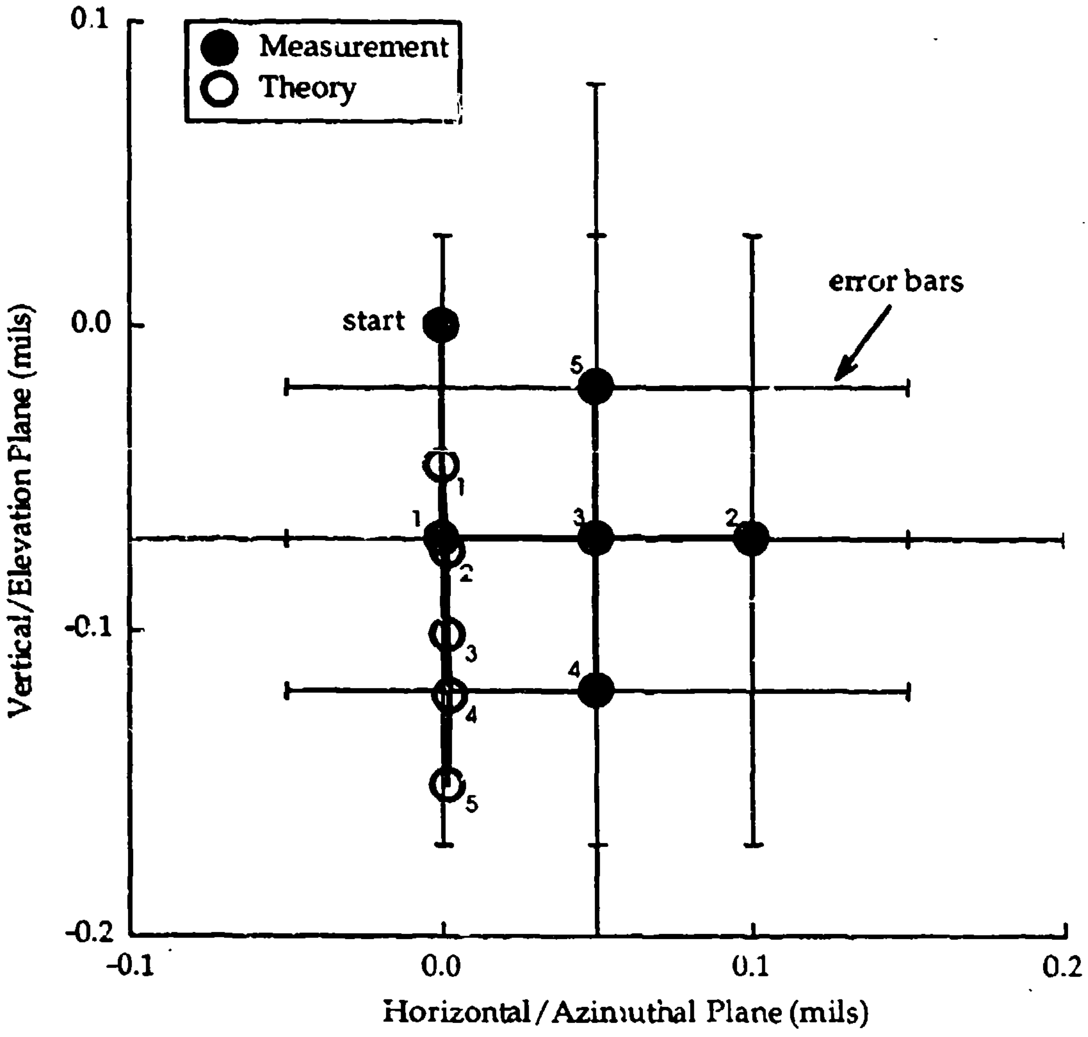

Figure 7. Predicted and Measured Muzzle Angle Change, One Minute after Firing each of Five DM13 Rounds (One Every Two Minutes) Through an M256 Barrel, Serial Number 4251

* Data was taken from a firing test done in November, 1991, APG, MD. Five DM13 rounds were fired through M256 barrel, serial number 4251 at a rate of roughly one round every two minutes.

5. SUMMARY

In theory, we have shown that thermal distortion of the gun barrel due to wall thickness variation in a typical M256 gun barrel is almost an order of magnitude smaller than the measured thermal distortion.

Thermal distortion due to uneven cooling accounts for most of the measured muzzle angle droop in our test case. However, for this particular barrel we observed changes in the horizontal muzzle angle which could not be accounted for in our analysis.

In view of our findings that wall thickness variation has a small effect on distortion, it seems unlikely that our a priori decision to neglect the wall thickness effect from that portion of the barrel which lies within the recoil mount would explain the noted differences.

There is, however, a third mechanism related to gun barrel manufacture, viz., variation in the chrome thickness, that could account for some of the differences between theory and experiment. Future work will add the contribution of chrome thickness variation to the predicted thermal distortion of Figure 7, in hopes of improving the agreement.

6. REFERENCES

1. Gerber, N., and M.L. Bundy, *Cross-Barrel Temperature Difference Due to Wall Thickness Variation*, ARL-TR-100, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, March 1993.

2. Gough, P.S., *The NOVA Code: A User's Manual - Volume 1. Description and Use*, IHCR-80-8, Naval Ordnance Station, Indian Head, MD, December 1980.

3. Chandra, S., and E.B. Fisher, *Simulation of Barrel Heat Transfer*, DAAA15-88-D-0014, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, June 1989.

4. Chandra, S., and E.B. Fisher, *Analysis of 16-inch/50 Gun Chamber Heating*, Veritay Report No. C68-1, Naval Ordnance Station, Indian Head, MD, October 1989.

5. Stratford, B.S., and G.S. Beavers, *The Calculation of the Compressible Turbulent Boundary Layer in Arbitrary Pressure Gradient - A Correlation of Certain Previous Methods*, No. 3207, Aeronautical Research Council R&M, 1961.

6. Bundy, M.L., *Gun Barrel Cooling and Thermal Droop Modeling*, To be Published, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD.

7. Boley, B.A., and J.H. Weiner, Theory of Thermal Stresses, New York; Wiley, 1960.